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(54) Apparatus for utilizing solar energy for the purpose of illuminating enclosed spaces not accessible to sunlight

(57) The invention provides apparatus for utilising solar energy for illuminating an enclosed space inaccessible to sunlight comprising a solar ray concentrator (1), one or more optical fibres (2) illuminated from the concentrator and one or more diffusers (3) for diffusing the light coming from the optical fibre(s) in the enclosed space. The concentration may comprise mirrors and the diffuser may be formed by divergence of the optical fibres.

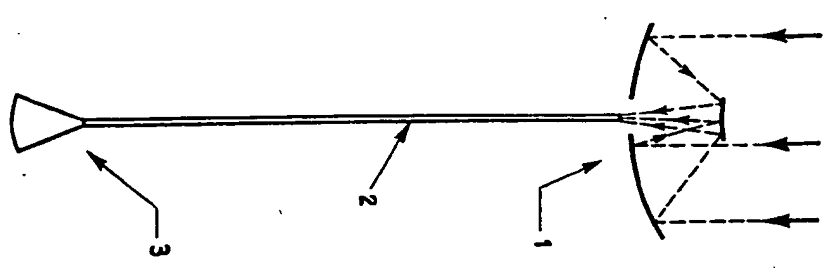

Fig 4

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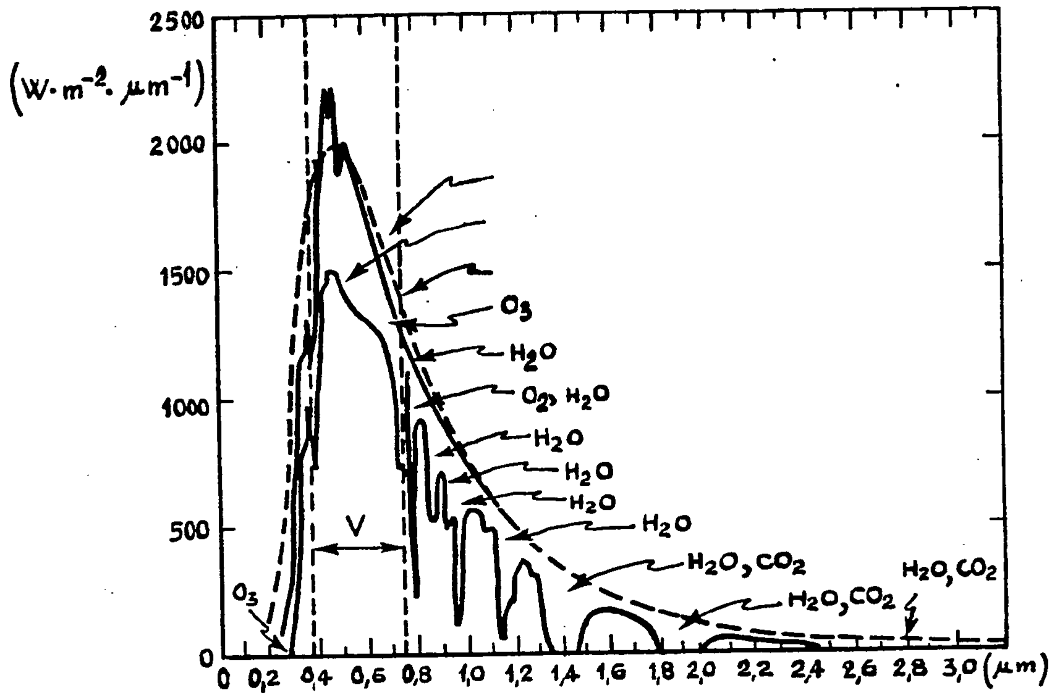

2500
(W·m⁻²·µm⁻¹)
2000
1500
1000
500
0
O3
H2O
O2, H2O
H2O
H2O
H2O
H2O
H2O, CO2
H2O, CO2
H2O, CO2
O3
V
0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 1,6 1,8 2,0 2,2 2,4 2,6 2,8 3,0 (µm)

Fig.1.

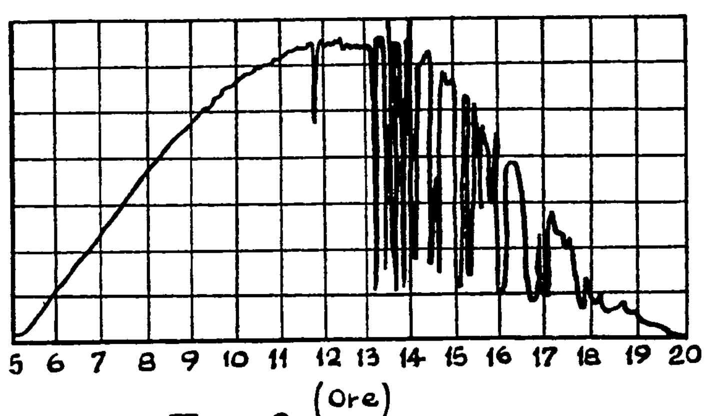
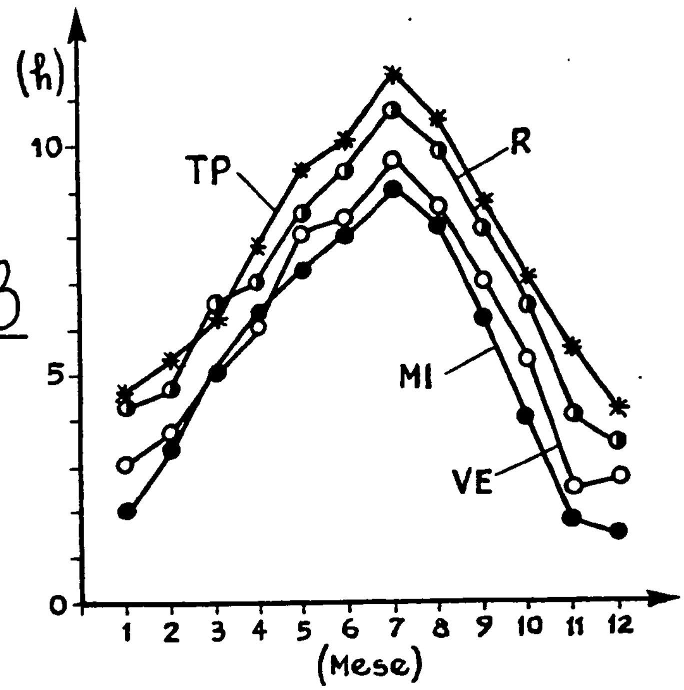

5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
(Ore)

Fig.2.

Fig. 3



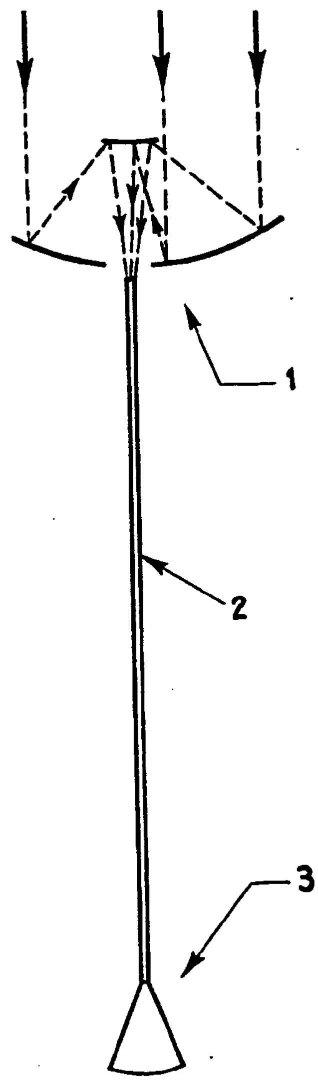


Fig 4

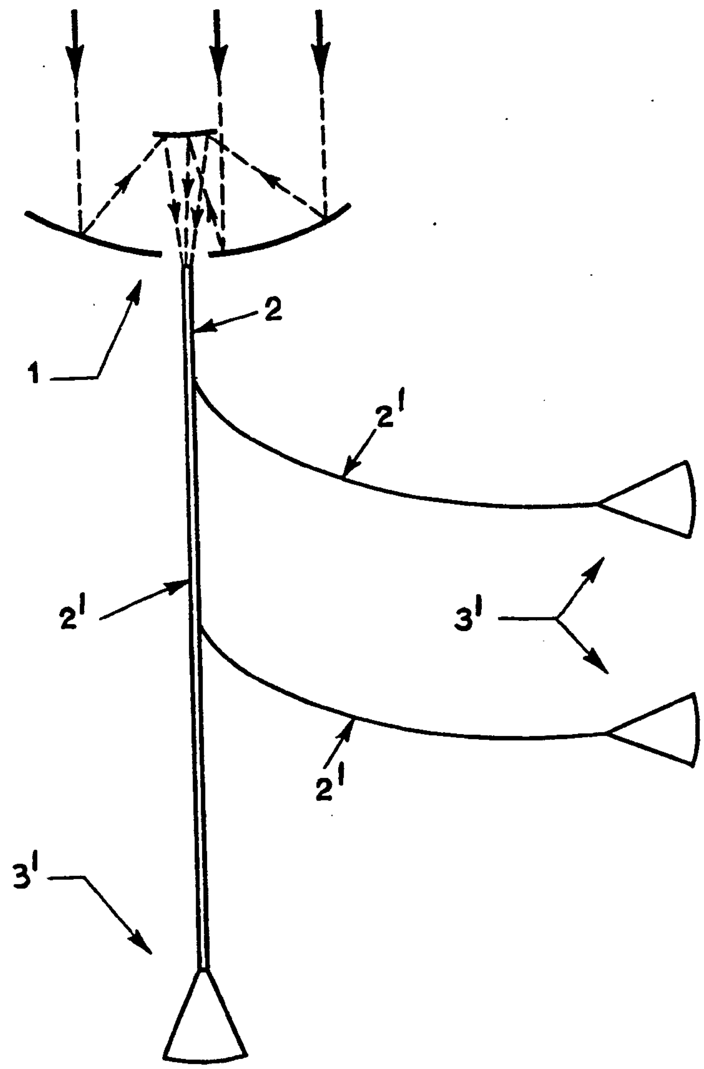


Fig. 5

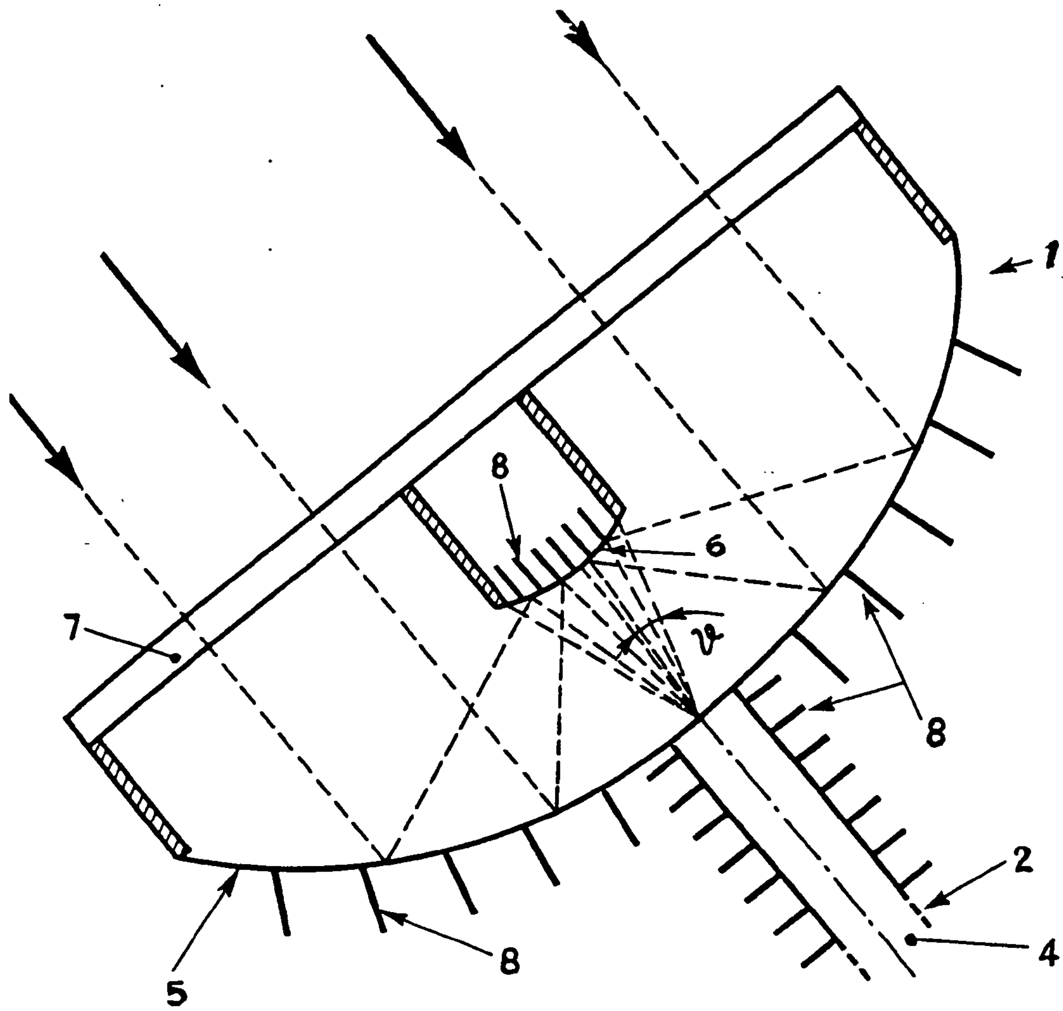


Fig.6

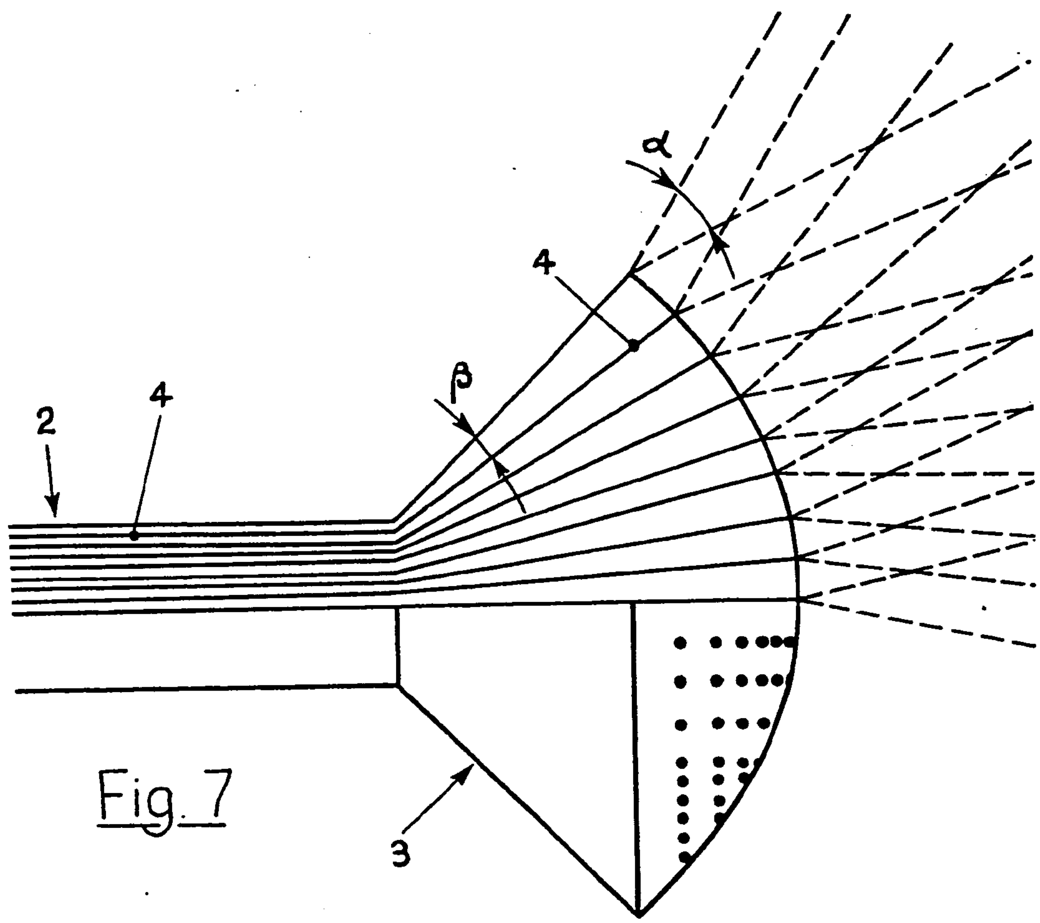


Fig. 7

SPECIFICATION

Apparatus for utilizing solar energy for the purpose of illuminating enclosed spaces not accessible to sunlight

It is known that the current energy crisis makes the study of alternative or subsidiary sources of energy such as, for example, solar energy, geothermal energy and other sources ever more attractive.

As regards solar energy in particular, the aim has been essentially the direct exploitation of heat (heating of rooms or enclosed spaces or furnaces) or the indirect exploitation of heat (generation of steam for actuating alternators).

Another practical use, however, may be the utilization of solar energy directly in the visible range for illumination purposes.

By this is meant the concentration, transport and distribution of a luminous flux for the illumination of enclosed spaces not accessible to sunlight.

In fact, a considerably percentage of electrical energy is used for illumination purposes even during daytime hours both in buildings used as offices and in other places such as large public places, motorway tunnels, underpasses and other enclosed spaces into which sunlight cannot penetrate.

It is well known, moreover, that the efficiency of a normal incandescent lamp is extremely low and of the order of 2.5% (luminous power, Wlum/electric power, Wel), because the major part of the radiated power is in the infra- red band. Fluorescent lamps have a better efficiency, 5.5% (Wlum/Wel), but an efficiency which is still very low. A great deal of energy is therefore wasted and therefore there is considerable advantage in effecting the illumination of enclosed spaces not exposed to sunlight by transporting solar luminous flux.

Another factor to be considered is that the power requirement for the illumination of dark enclosed spaces by day occurs practically simultaneously with the maximum requirements of industrial users, that is when the effective cost of energy is greater.

The object of the present invention is to render possible the utilization of solar energy in the "visible" range by means of elements which provide for the concentration, transmission and diffusion of this energy, on the basis of the use of optical fibres, for the purposes of illumination by day of enclosed spaces not directly accessible to sunlight.

It should be borne in mind that the term "optical fibre" is used in the present description in both the accepted meanings of: (a) a single light guide constituted as known by an inner core and an outer covering with a lower refractive index; and (b) an optical cable constituted by a plurality of individual fibres and provided with suitable coatings or sheaths and mechanical protections.

For the above-mentioned purposes, the present invention provides an apparatus for utilizing solar energy for the illumination of enclosed spaces not accessible to sunlight which is characterised in that it comprises a solar ray concentrator exposed to the sun, one or more optical fibres illuminated by the said concentrator, and one or more diffusers which provide for diffusing the light coming from the optical fibres in the said enclosed spaces.

Preferably, the concentrator is orientable in keeping with the position of the sun by means of a heliostat.

The optical fibres used in the apparatus according to the invention are especially optical multi-mode silicon fibres of the coated bundle type, with a constant attenuation for all the wavelengths comprised in the visible range.

The concentrator of the apparatus according to the invention may be a parabolic concentrator with mirrors with an external focus or a concentration with a Fresnel lens.

In turn, the diffuser of the apparatus according to the invention may be a diffuser having diffusing lenses and glass plates or an optical fibre diffuser.

The invention will now be described in greater detail with reference to the accompanying drawings, in which:

Figure 1 is a graph which shows the spectrum of the mean solar power as a function of the wavelength;

Figure 2 is a graph which represents the qualitative course of the specific mean power radiated by the sun in the span of a day;

Figure 3 is a graph which represents the course of the mean daily hours of sun as a function of the months of the year for a number of Italian cities and towns;

Figure 4 is a diagram of an apparatus according to the invention in the case where it comprises a single diffuser;

Figure 5 is a diagram of an apparatus according to the invention in the case where it comprises a plurality of diffusers (distribution network);

Figure 6 illustrates in detail an embodiment of the concentrator of the apparatus of Fig. 4 or of that of Fig. 5; and

Figure 7 illustrates in detail a diffuser of the apparatus of Fig. 4 or of the apparatus of Fig. 5.

It will be appropriate to preface the description of the apparatus according to the invention with some mention of the conditions in which it will have to work, that is of solar irradiation.

The spectrum of the mean solar power (in $Wm^{-2}\mu m^{-1}$) is given in Fig. 1, as has been said, as a function of the wavelength in μm.

The mean specific power of the entire spectrum, during the hours of insolation, is of the order of:

$$Em \simeq 185\ W/m^2$$

(with maximum values of the order of 1000 W/m^2 in correspondence with the maximum insolation).

Taking into consideration only the visible part v (wavelength 0.4–0.75 μm), however, the mean specific power becomes:

$$Emv = 100\ W/m^2$$

Fig. 2 shows the qualitative course of the mean specific power in the span of a day, first in the case of a clear sky and then in the case of the presence of disturbances.

It is obvious that the passage of disturbances causes sudden and appreciable reductions (even higher than 50%) which would be intolerable if they were to have repercussions in the illumination of rooms or enclosed spaces. In designing the apparatus according to the invention, it is therefore necessary to adopt means which obviate the more serious disadvantages of the variations in irradiation depending on the time of day and on disturbances, that is means which are capable of maintaining an almost constant level of illumination for at least 70% of the period of insolation.

The graph of Fig. 3 shows the course of the mean daily hours of sun as a function of the months of the year for a number of Italian cities and towns (in particular, Milan (MI), Venice (VE), Rome (R) and Trapani (TP).

The dispersion or spread between the four sample cities is relatively moderate; a mean daily value equal to 6 hours over the span of a year can be assumed.

This having been stated beforehand, let us now consider Fig. 4 to observe that the apparatus according to the invention is composed essentially of a solar ray concentrator 1 to be exposed to the sun, one or more optical fibres 2 in the form of a bundle which are illuminated by the concentrator 1, and a diffuser 3 for the light coming from the optical fibres in the space or room to be illuminated.

Fig. 5 shows an apparatus similar to that of Fig. 4, but in which there is provided a plurality of light diffusers 3′ and, consequently, a distribution network of optical fibres 2′ which start from the main optical fibre or fibres 2 which receives or receive the light from the concentrator 1.

It is obvious that the optical fibres play an important role in this apparatus, inasmuch as the installation thereof is possible by industrial methods: that is, there arises from their very use the possibility of flexible and effective application of the apparatus for enabling light to be transmitted to any enclosed space not illuminated by the sun.

Up to the present, optical fibres have found application principally in the transmission of signals. It is known, in fact, that the development of electro-optical systems for transmitting signals of analogue or digital type has stimulated a considerable improvement in the quality of optical fibres, above all in the range of the near infra-red ($\lambda = 0.75$ to 1.5 μm).

In this case, the material which gives the best performances is silicon.

Propagation in the visible range, on the other hand, has been used only over short distances (a maximum length of a few metres) where the attenuation, even if considerable, does not have an appreciable effect. Commercial fibres which best lend themselves to the transmission of visible light are quartz fibres.

The attenuation of fibres of this type is of the order of 1000 dB/km against the few dB/km of the better fibres used for communications

$$\text{(attenuation (dB)} = 10\ 1g_{10} \frac{\text{P input}}{\text{P output}}).$$

It has been found in accordance with the present invention, however, that it is possible to produce optical silicon fibres which present a moderate attenuation ≤ 50 dB/km which is practically constant in the range of the visible and of the near infra-red and which therefore

allow solar light to be transmitted with relatively low losses without introducing chromatic variations (white light). The fibres concerned are multimode silicon fibres with a wide core having a high numerical aperture which are placed close together to form a bundle constituted by very many individual fibres and having a diameter of some millimetres and suitably coated and protected. It is foreseeable that use of these fibres on a large scale will allow rapid industrialization thereof, with a consequent reduction in cost, which is high at present, and further technical improvements.

The use of the aforesaid optical multi-mode silicon fibres in the case of the apparatus according to the invention is decisive for achieving good practical results.

In fact, since the final degradation of all energy takes place in thermal form, the maximum power which can be transmitted along the optical fibre is linked essentially with the possibility of dispersing the various power losses without reaching temperatures too high for the fibre itself and, above all, for the other inert materials, such as possible cements and external sheaths.

By way of example, a bundle of fibres with an attenuation of 1 dB/m (1000 dB/km) in the visible range into which a luminous potential of 1000 W is introduced is called upon to disperse in the first metre a power of 260 W, a value which can be regarded as a maximum, assuming a maximum overtemperature of about 200°C, in the absence of forced ventilation.

On the other hand, a bundle of fibres with an attenuation of 0.05 dB/m (50 dB/km) would reach the maximum overtemperature with an input power equal to 26kW. It therefore seems clear that while in the first case the limitation of the maximum power which can be transmitted by the apparatus depends on the transmission losses along the fibres, in the second case (the said losses being much smaller) it derives from other factors, for example from the entrance losses, which are generally not less than 50% of the input power.

In the apparatus according to the invention which is shown diagrammatically in Figs. 4 to 7 it is now preferable to employ in practice a bundle 4 of optical multimode silicon fibres with wide core suitably protected and covered or coated (Figs. 6 and 7) and having the following characteristics:

number of optical fibers in the bundle:	550
material forming the optical fibers:	silica
core diameter of a single optical fiber:	200μm
functional diameter of the bundle:	5,3mm
packing coefficient of the bundle:	0, 78
numerical aperture of the fibers:	0, 19
constant attenuation for wavelengths comprised in the visible range:	0,35–0,75μm 20 db/Km

the bundle is provided with double plastic coating and with metal sheath.

The concentrator 1 of the apparatus according to the invention (Fig. 6) has its actual dimensions linked directly with the power it is intended to utilize, but has a configuration which is constant in principle. It comprises a parabolic outer mirrror 5, an inner mirror 6, a photochromatic glass plate 7, radiators 8 and a heliostat (or sun follower) not illustrated in the drawings.

The use of a double system of mirrors allows the beam of light to be better collimated, the focus to be obtained in an external position with respect to the main concentrator and the concentrated thermal energy to be reduced through passage via two successive surfaces. It may be necessary to make the mirrors from material reflecting visible radiation and transparent to infra-red radiation.

Photochromatic glass is characterized, as is known by the fact that it changes its transparency index as a function of the luminous power with which it is irradiated and therefore lends itself very well to the purpose.

More particularly, the transparency decreased therein on an increase in the luminous intensity. It therefore appears obvious that an element of this kind can be used for partial compensation of the variation in luminosity.

In concentrators of small dimensions the photochromatic glass plate may be positioned as a covering for the main parabola, while in those which are more extensive it must be positioned between the second parabola and the focus.

The presence of the radiators 8 is necessary in order to dissipate part of the heat energy in the case of concentrators of large dimensions. With suitable exchangers, utilization of this energy is possible (for example, for heating; in which case, the concentrator is a heat recovery concentrator).

Because of the limited dimensions of the focus, the aiming or pointing system of the concentrator must be very accurate.

It is therefore necessary to use a heliostat of servoassisted electronic type.

The concentration described is of the type having conventional parabolic mirrors.

Another possible solution (not shown) is based on the use of Fresnel lenses; these, as is known, are lenses having a flat inner surface and the outer surface, which is exposed to the sun, suitable shaped, the lenses being such as to concentrate the light beam passing through them at a suitable focus. The concentrator may be formed by means of a single lens or of several lenses, each coupled to a bundle of optical fibres. The Fresnel lenses could be made directly of photochromatic material. In general, the concentrator comprising Fresnel lenses has losses lower than those inherent in concentrators comprising mirrors.

It now remains to describe the diffuser 3 of the apparatus according to the invention. This element is necessary inasmuch as the beam of light, on leaving the optical fibre, appears with a rather narrow radiation lobe (aperture at half-value from 10 to 30°) which is insufficient by itself to ensure uniform illumination over a wide area.

The diffuser 3 may be of two types: a diffuser with optical fibres, like that shown in Fig. 7, or a diffuser with diffusing lenses and glasses (not shown).

The first type, which utilizes the actual aperture angle of each individual fibre, does not entail considerable additional losses and allows good diffusion, but requires a sophisticated technology. The second type, though causing losses to the extent of 30% of the input power, has the advantage of reducing the phenomenon of dazzle and does not present technological difficulties. Finally, local variation of the luminosity or brightness can easily be obtained by screening part of the luminous flux with a suitable opaque body.

In the practical embodiment illustrated in Fig. 7, the diffuser of the apparatus according to the invention provides for the optical fibres of the bundle which extend closely side by side through the bundle itself to be caused to diverge at their ends and to be held in this position by the use of a suitable inert cement. The very ends of the fibres constituting point sources of light are thus disposed over a curved surface from which each emits light at angles α which intersect as shown in Fig. 7, providing good diffusion of the light.

There may be many practical applications, of great interest, of the apparatus according to the invention. At this time, it is deemed appropriate to draw attention to the following among the principal applications:

(a) the diffuse illumination of large rooms or premises devoted to commercial, education, recreative, artistic and the like uses;

(b) the localized illumination of works of art in museums, churches and the like;

(c) the illumination of municipal underpasses, motorway tunnels and mine galleries;

(d) the illumination of enclosed spaces where the use of electric energy may be dangerous or in any case difficult;

(e) the execution of the shooting of films and the taking of photographs both outside and in the studio;

(f) illumination during undersea work;

(g) the creation of sources of "cold" light of high intensity for laboratory uses.

The apparatus according to the invention may be produced in the form both of a fixed installation and of a mobile installation.

In some cases, the illumination derived from solar energy may be integrated with conventional electric illumination. In correspondence with the period of insolation, however, it will be possible to achieve a substantial saving of energy. In other cases, in addition to the saving of energy, it will be possible to obtain considerable advantages in terms of safety, adaptability of use and high reliability.

In each case, subsidiary conventional electric lighting may conveniently be obtained by means of a single primary source of high power and high output disposed in parallel with the solar concentrator, with the use of the optical fibre system for distribution.

For a better understanding of the invention, there are given hereinafter some examples of design calculations for the application of the apparatus according to the invention to the solution of some practical problems. It is understood that these examples are not of a limitative nature.

Example I: *Illumination of an enclosed space*

Let it be assumed that a room 10×10m (100 m^2) to be used as an orifice must be illuminated; an illumination of *10,000 lumens* in photometric units (100 lumens/m^2 = 100 lux), equivalent to 10000/668 = *15 light watts* (radiometric units), is required.

The electric power necessary, with incandescent lamps, efficient 16 lumens/W, is: 10000/16 = 625 W.

On the other hand, considering solar illumination of the type described, we have the following:

— luminous power required	15 W
— power lost in the optical fibre diffuser (1 dB)	3.9 W
— power lost in the fibre (L = 10 m, att. = 0.05 dB/m, 0.5 dB)	2.3 W
— power lost at the input of the fibre (3 dB)	21.2 W
— power lost in the collector (3 dB)	42.4 W
— power required in the collector	84.8 W

In this case, therefore, a collector $\simeq 0.85\ m^2$ with a diameter $\simeq 1$ m is necessary.

By utilizing a photochromatic glass which allows variations up to 50% of the instantaneous luminosity to be compensated, the power required in the collector becomes 170 W, for which an area of 1.7 m^2 (collector diameter 1.5 m) is necessary.

In the latter case, the collector and photochromatic glass plate unit must disperse a maximum power equal to: $(185-100) \times 1.7 = 144$ W power in the infra-red not transferred, $85 + 42 = 127$ W, power dissipated in the photochromatic glass plate (in the period of maximum insolation) and in the concentrator. Total = 271 W.

On the other hand, by utilizing a Fresnel lens as concentrator and excluding the photochromatic glass plate, there would be obtained in the collector a loss of 0.5 dB, equal to 5.2 W, with a total required power of 47.6 W, obtainable with a lens having a diameter of 800 mm (or two 560 mm lenses).

Example II: *Illumination of a road tunnel*

The exploitation of solar energy is particularly convenient in this case because the illumination of the tunnel, above all in the initial sections, must be effected with an intensity proportional to the external illumination in order to avoid phenomena of dazzle or temporary blindness. This allows elimination of the levelling devices (photochromatic glass plates) with suppression of the corresponding losses.

In the central zone, on the other hand, the illumination can be maintained at a constant level, but with a moderate luminous intensity.

In this case, solar energy could be used advantageously for the sections close to the ends and conventional illumination could be used only in the central section.

Assuming it is desired to illuminate the initial zone (100 m) of a tunnel 6 metres wide by means of an optical fibre system, 60,000 lumens (100 lumens/m^2) are required. The corresponding total luminous power is therefore 90 light watts (3750 electric watts with incandescent lamps).

Considering, conservatively, transporting the entire power required over the whole length of fibre equal to 100 m, we have the following:

— luminous power required	90 W
— power lost in the optical fibre diffusers (1 dB $\times$ 5 diffusers = 5 dB)	195 W
— power lost in the fibre (L = 100 m, att. = 0.05 dB/m, 5 dB)	616 W
— power lost at the input of the fibre (3 dB)	901 W
— power lost in the collector (3 dB)	1802 W
— power required in the collector	3600 W

In this case, therefore, a collector $\simeq 36\ m^2$ having a diameter $\simeq 6.7$ m is necessary.

In order to avoid a collector of too large dimensions, which is the cause of considerable mechanical difficulties, groups of collectors of more moderate dimensions can be used.

The use of Fresnel lenses would allow the total collecting area to be contained in $\simeq 20\ m^2$.

It is understood that other embodiments of the apparatus described are possible, just as modifications in that illustrated and described are also possible, while still remaining within the scope of the present invention as is defined in the following claims.

CLAIMS

1. Apparatus for utilizing solar energy for the purpose of illuminating an enclosed space not accessible to sunlight, characterised in that it comprises a solar ray concentrator exposed to the sun, one or more optical fibres illuminated by the said concentrator, and one of more diffusers which provide for diffusing the light coming from the optical fibres in the said enclosed space.

2. Apparatus as claimed in claim 1, wherein the concentrator is orientable in keeping with the position of the sun.

3. Apparatus as claimed in claim 2, wherein the orientation of the concentrator is continuously controlled automatically by means of a heliostat of servoassisted electronic type.

4. Apparatus as claimed in any one of claims 1 to 3, wherein the optical fibres employed are optical multi-mode silion fibres of the coated bundle type, with a constant attenuation for all the wavelengths comprised in the visible range.

5. Apparatus as claimed in claim 4, wherein the said fibres are fibres with a wide core having a high numerical aperture which are placed close together to form a bundle constituted by very many fibres and having a diameter of some millimetres.

6. Apparatus as claimed in any one of claims 1 to 5, wherein the concentrator is a parabolic concentrator with mirrors with an external focus.

7. Apparatus as claimed in claim 6, wherein the concentrator is a parabolic concentrator with mirrors with an external focus which comprises an outer parabolic mirror, an inner parabolic mirror and a photochromatic glass entrance plate.

8. Apparatus as claimed in any one of claims 1 to 5, wherein the concentrator is Fresnel lens concentrator.

9. Apparatus as claimed in any one of claims 1 to 8, wherein a filter for the infra-red radiations is associated with the concentrator, the filter being associated if necessary with systems for recovering the heat inherent in the infra-red radiations.

10. Apparatus as claimed in any one of claims 1 to 9, wherein the diffuser is a diffuser having diffusing lenses and glasses.

11. Apparatus as claimed in claim 10, wherein the diffuser is a diffuser with optical fibres and wherein the fibres of the bundle which are illuminated by the concentrator are made to diverge at the arrival ends in a uniform distributed manner, the said ends being retained in a fixed position by an inert cement.

12. Apparatus as claimed in claim 1, substantially as described herein with reference to and as shown in Figs. 4, 6 and 7 or Figs. 5 to 7 of the drawings.

13. A method for illuminating an enclosed space not accessible to sunlight wherein there is used apparatus as claimed in any one of claims 1 to 12.

14. A method as claimed in claim 13, conducted substantially as described in either of the Examples.

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